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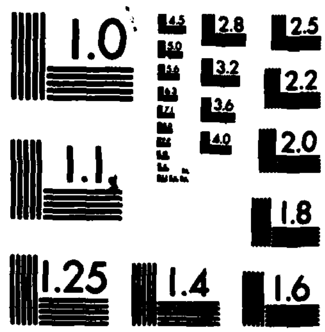

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An investigation was conducted to validate the potential of a pneumatic thrust deflector based on circulation control technology. This thrust deflector consists of a small blown curved surface mounted adjacent to a two-dimensional nozzle. In the configuration evaluated, a 3.5-in. (8.9-cm) -diameter blown surface was used to deflect the exhaust of a 660-lb (2.94-kN) thrust turbojet. Thrust deflection through 65 deg was achieved at reduced thrust levels. This performance was achieved pneumatically without the use of complex moving mechanical parts.

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NOTATION

A	Measured axial force, lb
F_N	Measured thrust without tangential blowing, lb
$\dot{m}$	Measured tangential blowing mass flow, slug/sec
$\dot{m}V_{slot}$	Tangential blowing jet momentum, lb
N	Measured normal force
P_d	Tangential blowing plenum total pressure, psi
P_∞	Ambient pressure, psi
R	Gas constant, 1715 ft lb/slug °R
T_d	Tangential blowing plenum temperature, °R
V_{slot}	Calculated tangential blowing jet velocity, ft/sec
θ	Thrust deflection angle, deg

ABSTRACT

An investigation was conducted to validate the potential of a pneumatic thrust deflector based on circulation control technology. This thrust deflector consists of a small blown curved surface mounted adjacent to a two-dimensional nozzle. In the configuration evaluated, a 3.5-in. (8.9-cm) -diameter blown surface was used to deflect the exhaust of a 660-lb (2.94-kN) thrust turbojet. Thrust deflection through 65 deg was achieved at reduced thrust levels. This performance was achieved pneumatically without the use of complex moving mechanical parts.

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INTRODUCTION

Several thrust deflection systems are currently under development for use in high-performance aircraft. These devices are intended for various applications such as increased maneuverability, heavy lift, or a short takeoff and landing (STOL) capability. Most of these thrust deflectors are complex mechanical devices which require numerous moving parts to operate in an adverse environment.

The circulation control thrust deflector is a mechanically uncomplicated pneumatic device. Downstream of a two-dimensional nozzle (Figure 1), a thin jet sheet is expelled tangentially over a curved surface. This jet sheet flows around the curved surface due to a balance between the centrifugal force and pressure force in the jet sheet. This effect is commonly known as the Coanda effect.

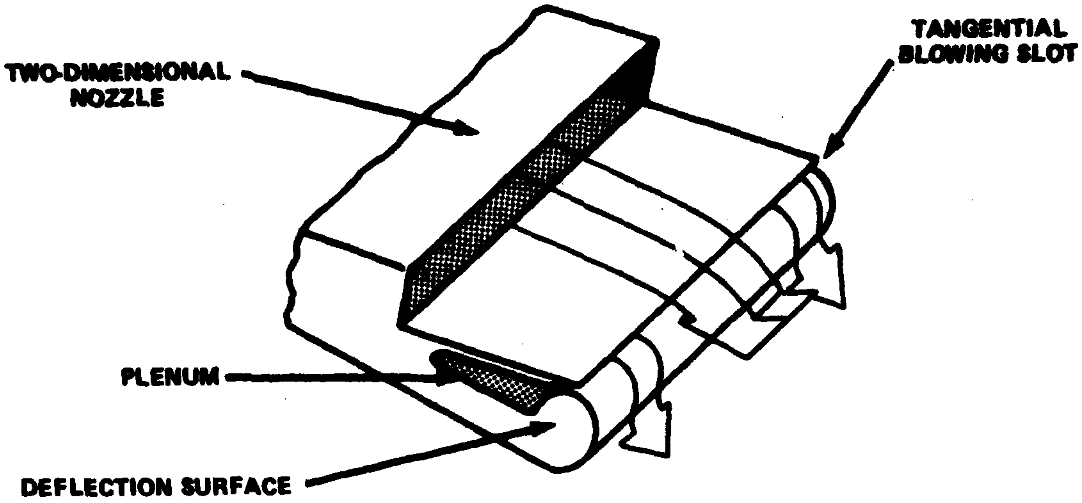


Figure 1 - Circulation Control Thrust Deflector

Exhaust from the turbojet expelled from the two-dimensional nozzle produces thrust. The exhaust moves aft and encounters the jet sheet at the slot. There is a reduction in the static pressure at the boundary between the exhaust and the jet sheet. The imbalance in the static pressure across the exhaust causes it to flow with the jet sheet around the curved, or thrust deflecting, surface. A force is recovered from the reduced static pressure around the deflecting surface. The deflected thrust is the sum of the nozzle thrust and this recovered pressure force.

The angle of thrust deflection is controlled pneumatically. Varying the blowing momentum of the jet sheet changes the distance that both the jet sheet and the turbojet exhaust flow around the thrust deflecting surface before separating. The farther around this surface both jets flow, the greater the thrust recovered on this surface and, therefore, the greater the thrust deflection.

This concept for thrust deflection was initially conceived in relation to an upper surface blowing (USB) configuration. In the circulation control wing/upper surface blowing (CCW/USB) high-lift system, turbofans are mounted over a circulation control wing.[1-4] Exhaust from the turbofans scrubs the upper surface of the wing and is turned pneumatically downward around the circulation control trailing edge (see Figure 2). In addition to thrust recovery the downward momentum of the propulsive jet enhances the wing generated lift.

*A complete list of references is given on page 19.

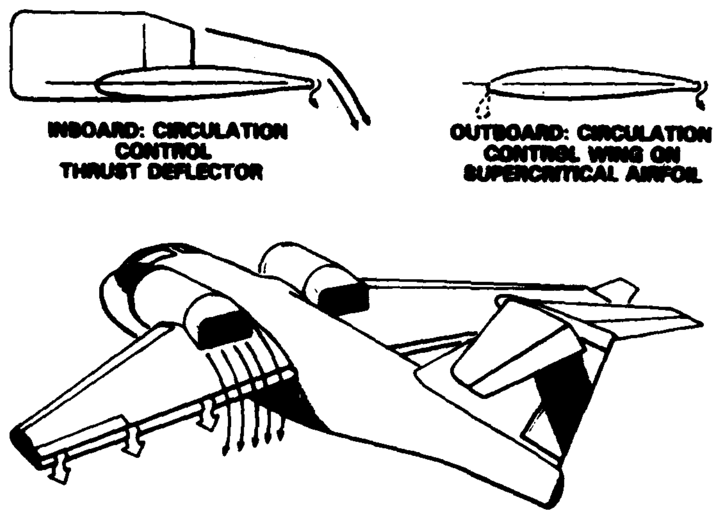


Figure 2 - Circulation Control Wing Upper Surface Blowing

One advantage of CCW/USB over conventional USB systems is the simple fixed trailing edge of the circulation control wing. There is no complex multi-element mechanical flap system as in conventional USB systems. Elements of the CCW/USB high-lift system were evaluated statically on the NASA Quiet Short-Haul Research Aircraft (QSRA).[5]

The circulation control thrust deflector is a configuration more adaptable to high-performance aircraft than CCW/USB. In this pneumatic thrust deflector the circulation control wing is reduced to a small blown curved surface which spans a two-dimensional nozzle as shown in Figure 1. Being compact, it can be used in more conventional engine locations. Like CCW/USB it shares the advantage of being a pneumatic device with few moving parts.

In high-performance aircraft this pneumatic thrust deflector must effectively turn the high pressure exhaust of a turbojet. Therefore, a static investigation was conducted to validate the thrust deflecting capability of the circulation control thrust deflector when employed with a turbojet.

MODEL AND TEST DESCRIPTION

A small turbojet, the J402-CA-400, was employed to generate the hot high pressure exhaust jet. The uninstalled characteristics of this turbojet are

presented in Table 1. Aft of the turbojet was mounted one of a pair of interchangable ducts. These ducts transitioned from a round inlet to a two-dimensional exit. One duct had an aspect ratio 4 exit and the other an aspect ratio 7 exit. Both ducts had the same 29-in^2 (186-cm^2) exit area, which was the exit area of the fixed nozzle of the turbojet. Designing two-dimensional nozzles was not part of this investigation. These ducts were not intended to provide optimum performance but only to provide a means to vary the aspect ratio of the exhaust jet. The installed performance of the turbojet with the two-dimensional nozzle is presented in Figure 3.

Table 1 - Turbojet Characteristics

Designation	J402-CA-400
Type	Single shaft turbojet
Compressor	Single transonic axial compressor with a single centrifugal compressor, Max airflow 9.6 lb/sec (4.35 kg/sec), Pressure ratio 5.8
Turbine	Single stage axial
Performance	Max sea level static thrust 660 lb (2.94 kN) at 41,200 rpm

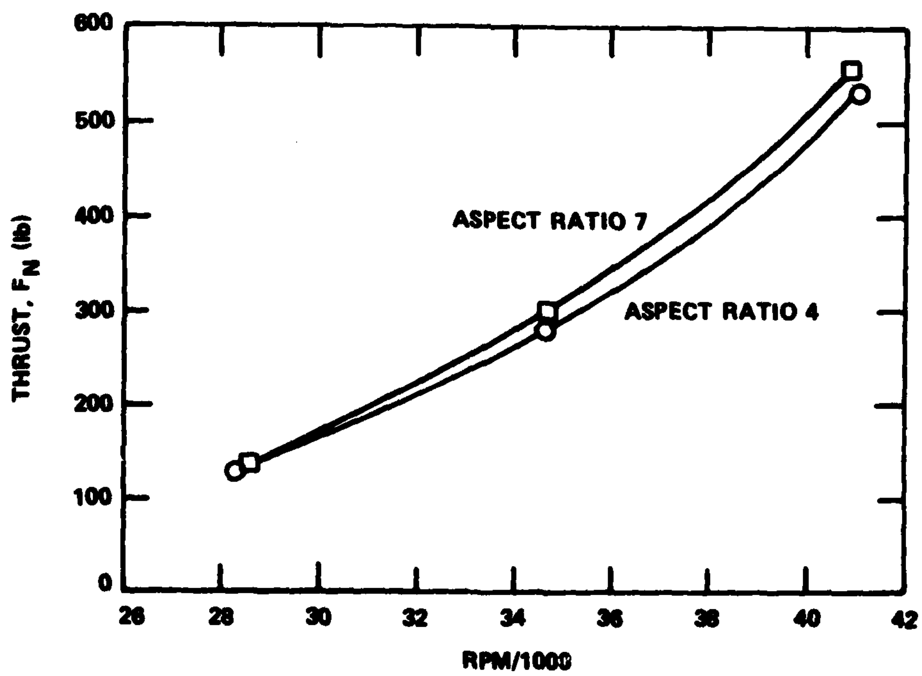


Figure 3 - Installed Thrust Characteristics

The cylindrical thrust deflecting surface had a diameter of 3.5 in. (8.9 cm) and could be mounted in one of three positions downstream of the nozzle duct, 0, 5, 10 in. (0, 12.7, 25.4 cm) aft of the nozzle. These positions correspond to 0, 0.82, and 1.64 equivalent nozzle diameters. A flat plate extends from the nozzle out to the thrust deflecting surface forming the slot through which the jet sheet is expelled. The span of the slot was 17.5 in. (44.5 cm) with flow fences at each end of the slot.

The turbojet with a bellmouth inlet, the nozzle duct, and the thrust deflecting surface were all suspended from a six-component balance. Forces measured with this balance were used to calculate the thrust recovery and angle of deflection. This arrangement is shown in Figure 4.

In addition to forces measured by the balance, the temperature (T_d), pressure (P_d), and massflow ($\dot{m}$) of the jet sheet were also measured. The temperature and pressure were used to calculate the velocity of the jet shet by the equation:

$$V_{slot} = \left\{ 2RT_d \left(\frac{\gamma}{\gamma - 1}\right) \left[1 - \left(\frac{P_\infty}{P_d}\right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{\frac{1}{2}}$$

This equation assumes isentropic expansion to ambient conditions.

Data were recorded at constant engine rpm while the blowing momentum of the jet sheet ($\dot{m}\, V_{slot}$) was varied. Values of rpm held constant were 70, 85, and 100 percent maximum rpm. The maximum value achieved with the two-dimensional nozzle installed was 40,800 rpm. Thrust deflection was evaluated with the deflecting surface at each of the three distances downstream of the nozzle for each thrust value.

DISCUSSION OF RESULTS

Effective thrust deflection requires a high percent of thrust recovery over a wide range of thrust deflections. The limits of this range of thrust deflection are defined by the particular purpose for which the thrust deflector is employed. Increasing the maneuverability or lifting capability of an aircraft can require less than 20 deg of thrust deflection. Thrust deflections above 20 deg may be required for some STOL configurations. The circulation control thrust deflector has the potential to achieve either degree of performance at specific thrust-to-blowing ratios.

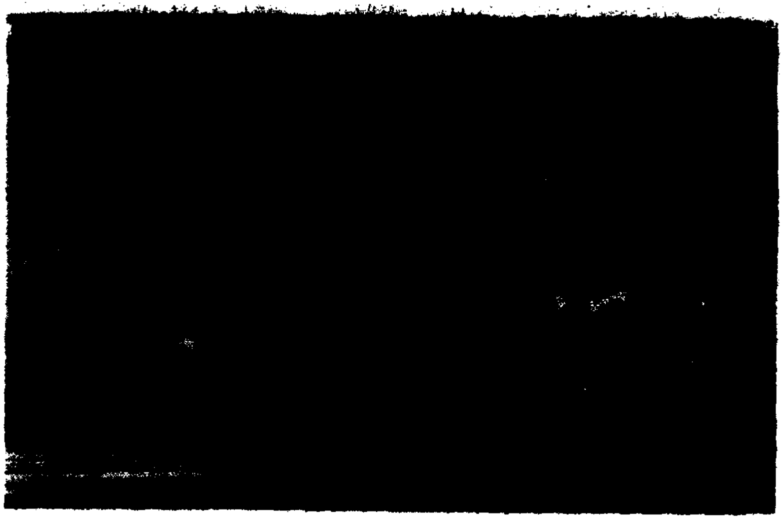


Figure 4a - Bellmouth Inlet, J402-CA-400 Turbojet and Two-Dimensional Nozzle Suspended from Six-Component Balance

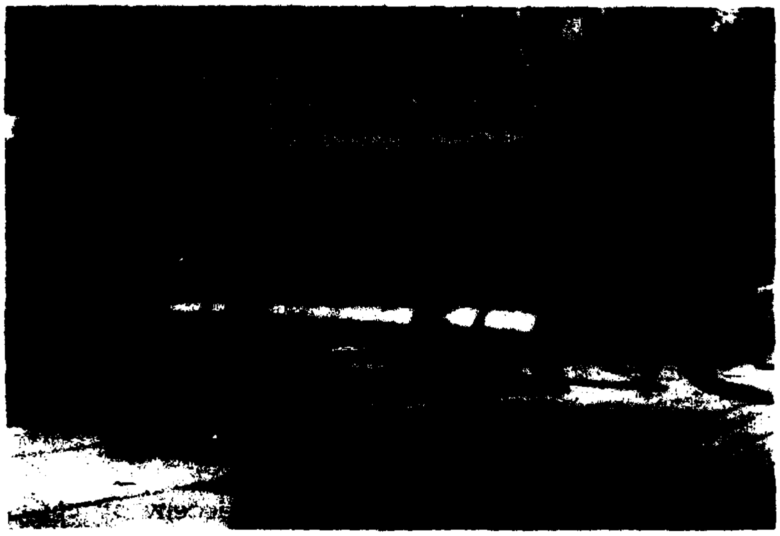


Figure 4b - Cylindrical Thrust Deflecting Surface and Two-Dimensional Nozzle

Figure 4 - Circulation Control Thrust Deflector Model

The thrust deflection angle (θ) was determined from the measured net normal force (N) and net axial force (A) by the relationship:

$$\theta = \tan^{-1}\left(\frac{N}{A}\right)$$

The thrust deflection resulting over a range of tangential blowing momentum ($\dot{m}V_{slot}$) is presented in Figures 5 and 6. Deflections achieved with the aspect ratio 4 nozzle are presented in Figure 5, while Figure 6 represents the performance with the aspect ratio 7 nozzle.

The percent of the thrust recovered, or thrust deflecting efficiency, is also presented in Figures 5 and 6. Thrust recovery was based on the total system force. This includes both the measured nozzle thrust (F_N) and the calculated tangential blowing mementum ($\dot{m}V_{slot}$). Nozzle thrust was measured without tangential blowing ($\dot{m}V_{slot} = 0$) and assumed constant for constant rpm.

Several performance characteristics of the pneumatic thrust deflector are illustrated in Figures 5 and 6. As previously indicated, thrust deflection is controlled pneumatically. Following any one line of constant thrust in these figures illustrates how thrust deflection varies with the tangential blowing momentum. Increasing the tangential blowing momentum results in greater thrust deflection.

The thrust recovery portion of these figures indicates decreasing thrust recovery as the angle of deflection increases. Also, for the same thrust deflection higher thrust recovery was achieved when the thrust deflecting surface was positioned downstream of the two-dimensional nozzle.

Comparing the three lines of constant thrust in each figure shows that for a constant blowing momentum the thrust deflection increases as the thrust decreases. The higher the thrust the lower the pressure that must be generated in the exhaust as it turns around the thrust deflecting surface to achieve the same thrust deflection. Lower pressures are achieved by increasing the tangential blowing momentum.

Thrust deflection also improved when the deflecting surface was positioned downstream of the two-dimensional nozzle. Comparing the maximum deflection

achieved with the deflecting surface at each of the three downstream positions shows better performance was achieved when the tangential blowing slot was at either 5 or 10 in. (12.5 or 25.4 cm) aft of the nozzle. In part, this effect is due to the influence of the unblown ($\dot{m}V_{slot}$ = 0) deflecting surface on the exhaust. With the slot at the nozzle exit, the unblown thrust deflection had a negative value. The unblown thrust deflection with the slot downstream of the nozzle had a positive value. In addition to the influence of the unblown deflecting surface, the core of the exhaust is more diffuse downstream. The diffuse exhaust flows more readily around the deflecting surface.

The effect of nozzle aspect ratio is presented in Figure 7. A similar range of thrust deflection is achieved with either nozzle. The difference in performance was in the percent thrust recovery. Thrust recovery was better with the aspect ratio 7 nozzle.

The aspect ratio 7 nozzle 10-in. upstream of the slot provided the highest performance. At a thrust of 135 lb the range of thrust deflection varied from 6 through 65 deg with better than 85-percent thrust recovery. The range of thrust deflection for 530 lb of thrust varied from 2 through 11 deg.

Maximum thrust deflection at the higher thrust levels suffered from over expansion of the tangential blowing slot. Several of the curves in both Figures 5 and 6 show decreasing thrust deflection with increasing tangential blowing. An example of this effect is the 530-lb thrust curve in Figure 6a. Thrust deflection (θ) increases as the tangential blowing momentum ($\dot{m}V_{slot}$) increases from 0 to 20 lb. For values of $\dot{m}V_{slot}$ between 20 and 30 lb, there is little change in the angle of thrust deflection. Above a value of $\dot{m}V_{slot}$ equal to 30 lb, the thrust deflection decreases as the blowing momentum increases.

When the slot height exceeds 5 percent of the radius of the thrust deflecting surface, the thin jet sheet separates prematurely from the deflecting surface. Due to thermal expansion and the pressure in the tangential blowing plenum, the height midway across the slot did exceed this value; therefore, the optimum thrust deflection was not achieved. An indication of the range of deflection that might be achieved is presented in the appendix.

SUMMARY OF RESULTS

The investigation validated the potential of a pneumatic thrust deflector based on circulation control technology. This investigation demonstrated the following:

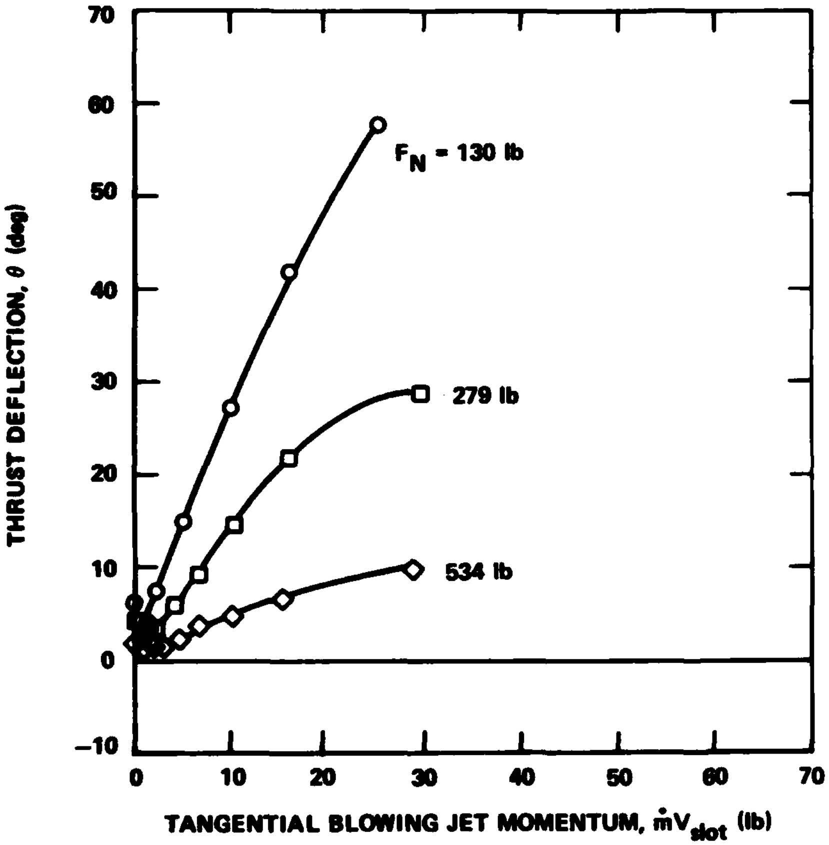
1. The combination of a two-dimensional nozzle with tangential blowing over a cylindrical deflecting surface can pneumatically control thrust deflection.
2. Thrust deflection through 65 deg was achieved with 85-percent thrust recovery at reduced thrust.
3. At maximum thrust, 11 deg of thrust deflection was achieved with 95-percent thrust recovery.
4. The maximum achievable deflection increased when the thrust deflecting surface was one or more equivalent nozzle diameters downstream of the two-dimensional nozzle.
5. The aspect ratio 7 nozzle provided higher thrust recovery than the aspect ration 4 nozzle.

RECOMMENDATIONS

The investigation documented in this report has demonstrated the capability to pneumatically deflect the thrust of a turbojet with a thrust deflector based on circulation control technology. The concept requires further parametric evaluation to determine optimum configurations based on required performance.

Future investigation should include configurations previously evaluated as circulation control airfoils. An extensive data base for circulation control airfoils has been collected. This data base could be used in the design of pneumatic thrust deflector configurations after the similarities in the aerodynamics of both concepts are evaluated.

Figure 5 - Thrust Deflection and Thrust Recovery with Aspect Ratio 4 Nozzle



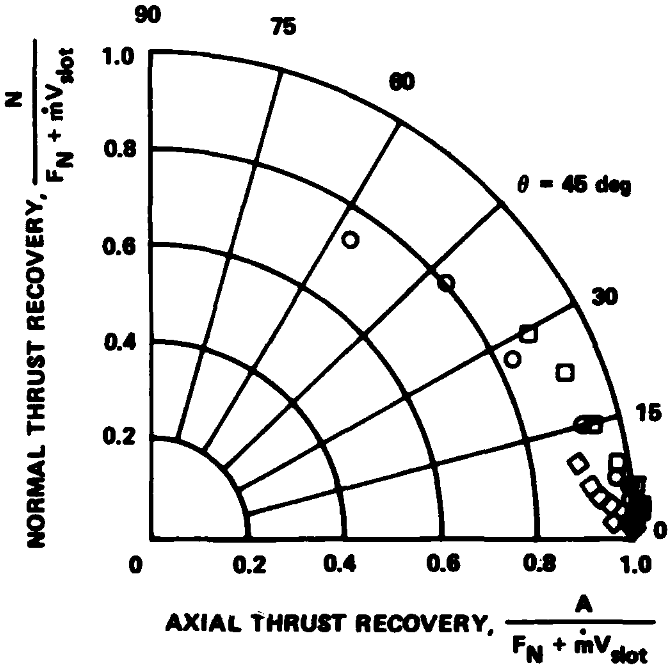


Figure 5a - Tangential Blowing Slot 10 Inches Aft of Nozzle

Figure 5 (Continued)

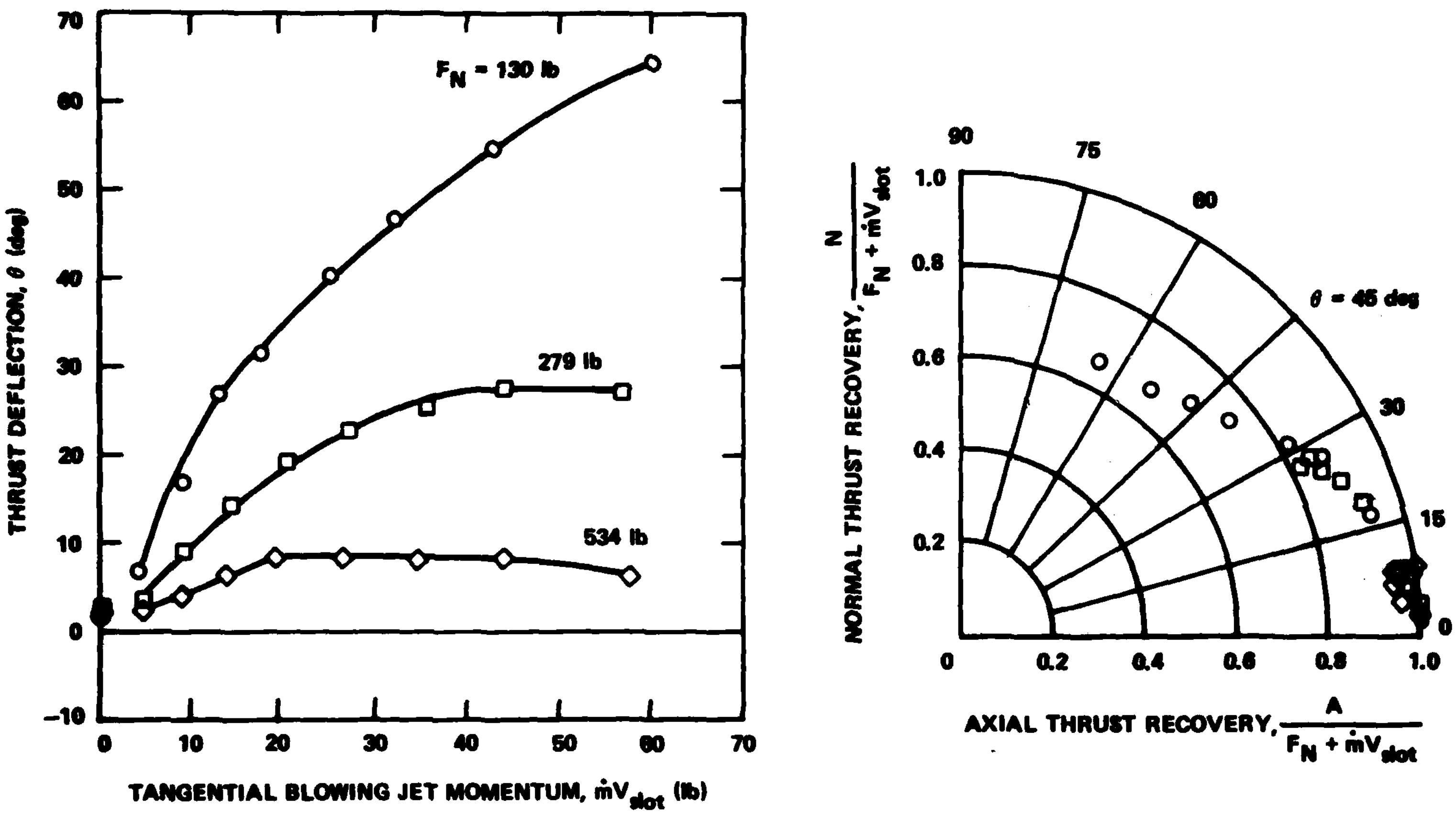


Figure 5b - Tangential Blowing Slot 5 Inches Aft of Nozzle

Figure 5 (Continued)

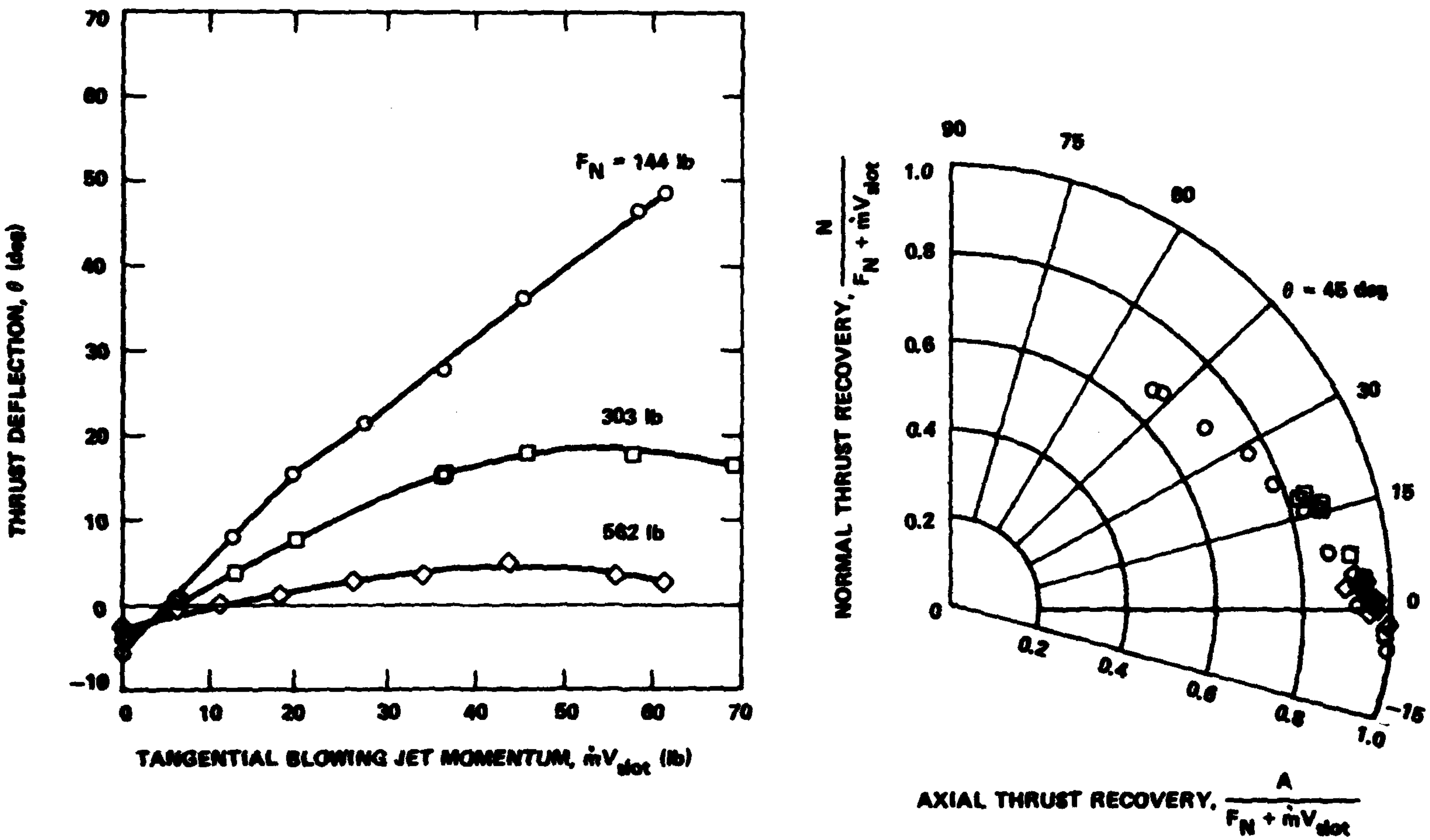


Figure 5c - Tangential Blowing Slot at Nozzle Exit

Figure 6 - Thrust Deflection and Thrust Recovery with Aspect Ratio 7 Nozzle

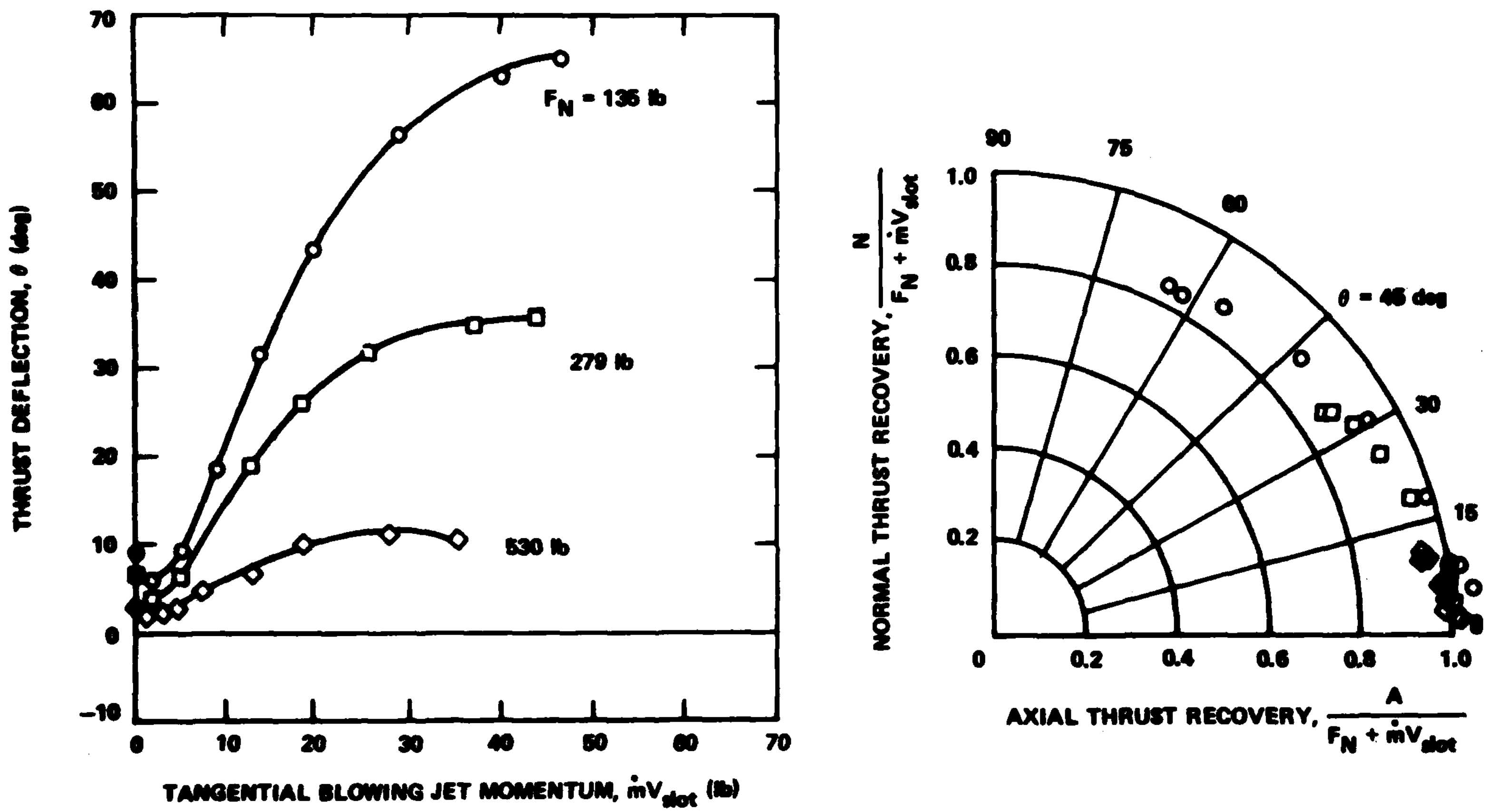


Figure 6a - Tangential Blowing Slot 10 Inches Aft of Nozzle

Figure 6 (Continued)

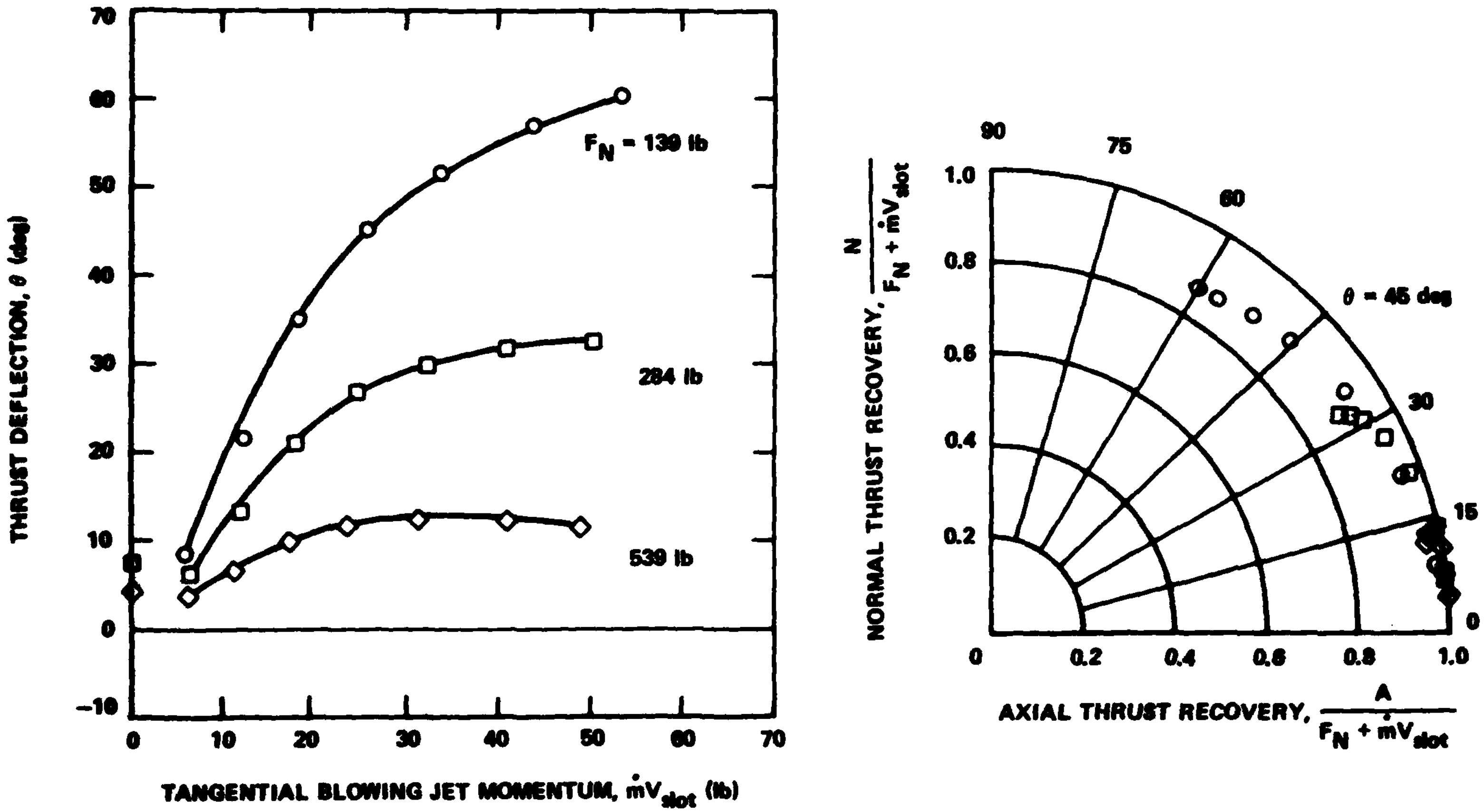


Figure 6b - Tangential Blowing Slot 5 Inches Aft of Nozzle

Figure 6 (Continued)

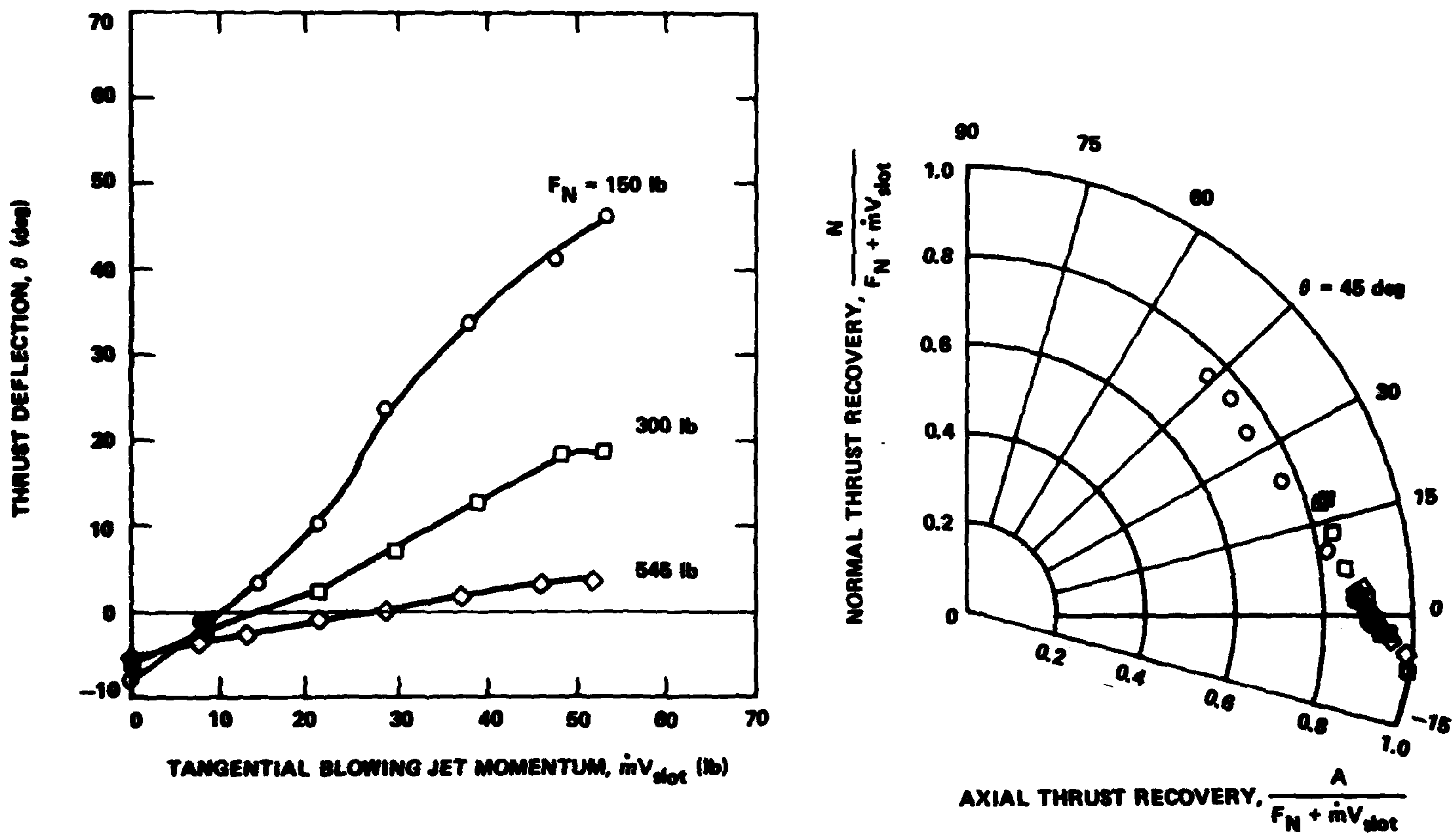


Figure 6c - Tangential Blowing Slot at Nozzle Exit

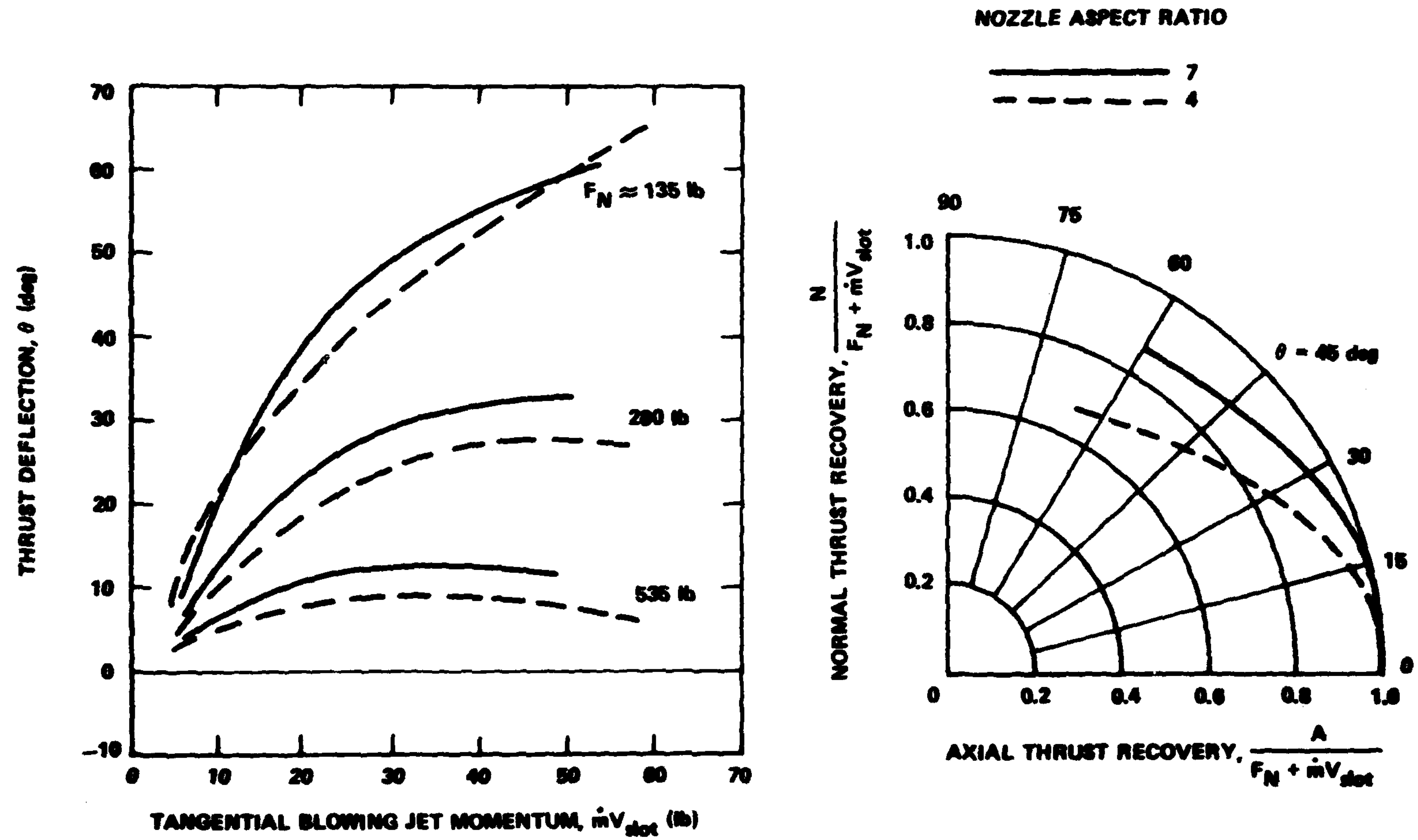


Figure 7 - Effect of Nozzle Aspect Ratio on Thrust Deflection and Thrust Recovery

(Tangential blowing slot 5 in. aft of nozzle)

APPENDIX

The circulation control thrust deflector was also evaluated using a small turbofan simulator. One configuration evaluated had an aspect ratio 4 nozzle with an exit area of 24 $in.^2$ (153 cm^2). This combination of nozzle and turbofan simulator produced a maximum static thrust of 92 lb (0.41 kN).

A blown cylindrical thrust deflecting surface was used to pneumatically deflect the exhaust of the turbofan simulator. The diameter of the cylindrical surface was 1.75 in. (4.45 cm). This was half the diameter of the thrust deflecting surface evaluated with the small turbojet.

The tangential blowing slot of the thrust deflecting surface was 11.3 in. (28.7 cm) downstream of the two-dimensional nozzle. Thrust deflection achieved with this configuration is presented in Figure A.1.

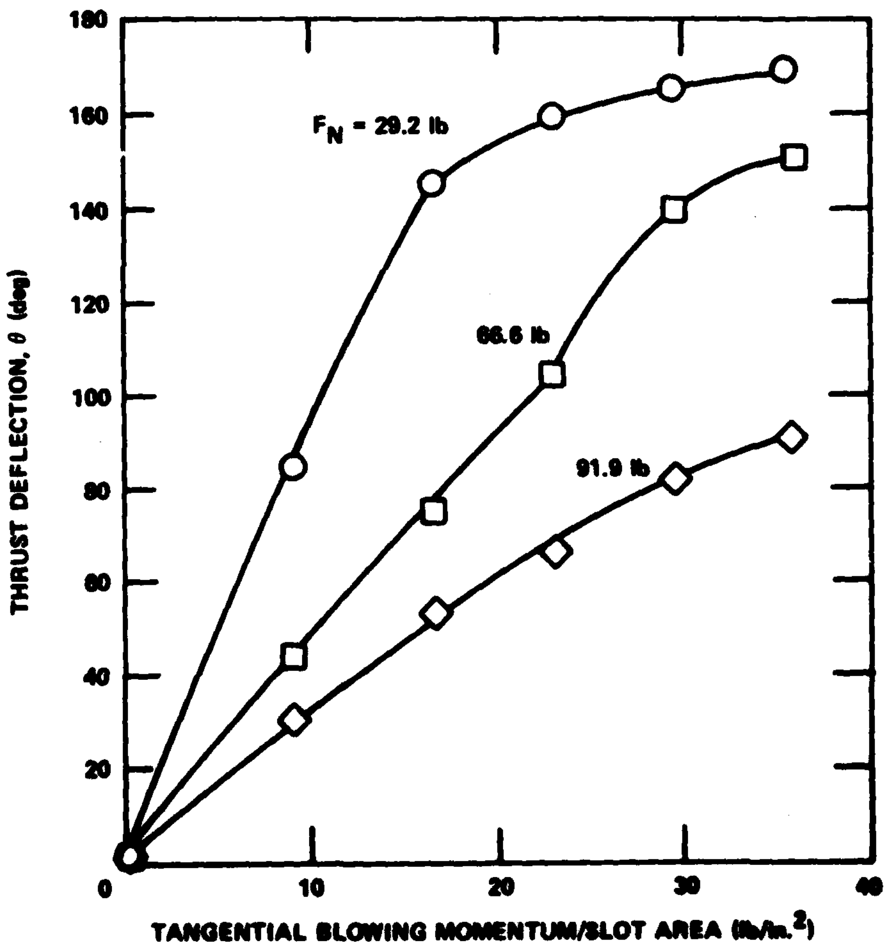


Figure A.1 - Thrust Deflection with 1.75-Inch-Diameter Deflecting Surface and Turbofan Simulator

Trends in the trust deflecting capability achieved in this cold exhaust gas were also demonstrated with the hot exhaust gas from the small turbojet. Thrust deflection increased as the tangential blowing momentum increased. Maximum thrust deflection decreased as the thrust increased.

Significant of the performance achieved in the cold exhaust gas is the magnitude of the maximum deflection. For an average thrust of 91.9 lb (0.41 kN), the range of thrust deflection achieved was from 1 through 92 deg. This was achieved with the smaller diameter deflecting surface. This performance suggests the potential of a pneumatic thrust deflector. It also suggests that had the problem with slot height not occurred, the maximum thrust deflection achieved in the hot gas evaluation might be significantly higher. Further evaluation of the pneumatic thrust deflector is needed to determine the full potential of the system.

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